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Preface: Landslide–transport network interactions

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1 Introduction

This special issue consists of 11 publications focussed on landslide–transport network interactions. Across a range of environments, landslides and transport networks are inherently interlinked both in terms of process (e.g. slope modification increasing the probability of landslides) and impacts (e.g. landslides blocking transportation networks). In this preface we describe four research challenges for better understanding landslide–transport network interactions that are addressed by the 11 publications that constitute this special issue and research from the broader community. These four research challenges consist of the following: (i) accessing records of landslides, (ii) better understanding landslide susceptibility, (iii) methods addressing the unique setting of transport networks in steep topography and (iv) future drivers of landslide transport interactions.

Transportation networks can broadly be considered to include roads, railways, waterways, pipelines, air transport and cables, although the majority of work in this special issue focusses on roads and railways. The impacts of landslide on transportation networks include delays and detours, damage to vehicles and transportation infrastructure, and increased cost of maintenance (Postance et al., 2017). Impacts may be direct (such as a landslide directly landing on a road surface) or indirect such as loss of income to a region due to inaccessibility (Winter et al., 2016).

Systematic regional and global databases of landslides are limited (Wood et al., 2020; Guzzetti et al., 2012), but one conservative estimate is that $\sim 11.7\,\%$ of all landslides in a global database of non-seismically triggered landslides between 2004 and 2016 affected road networks (Froude and Petley, 2018). However, these and similar statistics are likely to underestimate the magnitude of impact and interactions between landslides and transportation networks due to (i) under-reporting of landslides and (ii) the potentially large regional implications of a landslide blocking a transportation corridor (e.g. Meyer et al., 2015), under-evaluating the potential impact of road networks on water and sediment flow paths at the catchment scale (Sidle and Ziegler, 2012; Tarolli and Sofia, 2016).

Landslide–transport network interaction research – spanning a range of disciplines including geomorphology, remote sensing, spatial analysis, economics, and engineering – is generally across three areas:

i. *Understanding the physical processes of landslide and transport interactions.* Examples of methods include remote sensing (Giordan et al., 2018), spatial analysis of landslide inventories and road networks (Donnini et al., 2017), landslide susceptibility mapping (Brenning et al., 2015; Meneses et al., 2019), landslide models (Santangelo et al., 2019), and measurement of landslide flows (Sidle et al., 2014).

ii. *Understanding the impacts of landslides on transportation network.* Examples of methods include forensic analysis of costs (Klose et al., 2016), economic impact modelling (Klose et al., 2015; Jaiswal et al., 2010), traffic impact modelling (Meyer et al., 2015), and modelling spatial and temporal changes to meteorologically triggered landslides under climate change in road corridors (Uzielli et al., 2018).

iii. *Mitigation of transportation network landslide hazard, exposure, vulnerability and overall risk.* Methods span both physical and planning measures and include minimising exposure by monitoring/early warning coupled with road closure systems (Graziella et al., 2015; Ferrigno et al., 2017), minimising hazard by slope engineering to reduce landslide susceptibility (Fowze et al., 2012), calculation of acceptable risk (Mignelli et al., 2012) and risk-adapted planning for siting of new roads (Lennartz, 2013).

The main purpose of this preface is an introduction and summary of the 11 papers published as part of this special issue. We have organised these papers into four themes, relating to four research challenges we believe are important to better understand landslide–transport network interactions:

- Challenge 1 – *compilation of and access to landslide occurrence and impact records*: access to long-term, substantially complete records of landslides and their impacts at a range of spatial and temporal scales. This challenge covers the issues of both (a) systematic data collection and (b) data sharing and management.
- Challenge 2 – *better understanding of links between landslide susceptibility and physical processes*: integrating broad-scale regional landslide susceptibility with more local-scale interactions between transport networks and landslide susceptibility. Developing a more nuanced understanding of different transport network types and their different interactions with landslide processes, with a particular focus on human actions such as informal road building, long-term maintenance, and competing priorities such as economic development.
- Challenge 3 – *appropriate approaches to deal with the unique setting of mountain transport networks*: building and maintaining transportation networks in steep topography is challenging but vital for connecting remote communities to development opportunities. This requires approaches to understand the balance of risk and opportunity.
- Challenge 4 – *understanding future drivers of landslide –transportation network interactions*: better planning of existing and new transportation networks requires an understanding of both (i) future changes of drivers of landslides (i.e. climate change) and (ii) future expansion of transport networks, particularly in the Global South.

This special issue aims to contribute to our understanding of these four challenges. In the next section of this preface to the special issue (Sect. 2), we outline each of these challenges in more depth with reference to the broader literature and describe the contribution to knowledge of the 11 papers of this special issue on landslide–transport network interactions.

2 Research challenges addressed in this special issue

2.1 Challenge 1: access to landslide occurrence and impact records

Access to substantially complete landslide inventories is a challenge faced by the landslide community as a whole. Landslide inventory/database compilation methods (e.g. field surveying, remote sensing, archive) often have challenges surrounding completeness (e.g. Guzzetti et al., 2012) and may be spatially biased towards areas where landslides are easily observable or have affected humans, such as roads (e.g. Santangelo et al., 2010), which makes it difficult to definitively assess the scale of influence of transport network building upon landslide occurrence in comparison to surrounding areas.

In addition, the fact that the shift from hazard- to risk-based forecasting is relatively recent might explain why records of landslide impact on transportation networks are relatively short and unsystematic (Klose et al., 2014; Taylor et al., 2015). If impact is recorded at all, this may be done by different organisations (e.g. highways agencies) and only outline the primary physical impact rather than the secondary regional disruptions to the transportation network (Winter et al., 2016). As a result of incomplete records, it is likely that we are underestimating the influence of transport networks on landslide occurrence and the impact of landslides upon the transport network. Two papers in this special issue address this challenge of access to records:

- Voumard et al. (2018) attempt to address this challenge by developing a detailed database of landslides occurring on Swiss roads and railways over a 5-year period using digital news alerts. Their work particularly emphasises the importance of small landslides ($< 10\,\mathrm{m}^3$ volume of deposit) that occur along roads and railways, which may not meet thresholds (e.g. number of fatalities) for being recorded in other databases. Voumard et al. (2018) find along these road or railway transportation networks that small landslides ($< 10\,\mathrm{m}^3$) comprised 95 % of all events in their database and 75 % of the total direct cost of landslide impact to the transportation network each year. This finding departs from previously established landslide frequency-size statistics (e.g. Malamud et al., 2004), possibly indicating different processes governing landslide size along transportation networks compared to landslide processes at a broader regional scale. This work highlights the importance of systematically assessing all landslides that occur along roads or railways in a region and gives insight into the potential use of digital news for recording the impact of landslides.
- Ali et al. (2019) outline the construction of a landslide susceptibility map for the Karakoram Highway in Pakistan, using a novel approach to creating a landslide in-

ventory from road clearance logs. Their research shows how in a data-poor environment, where access to substantially complete regional landslide inventories may not be possible, road corridors may be relatively data-rich for understanding landslide processes and constructing a susceptibility map in the road corridor. Ali et al. (2019) found that 60 % of the highway fell into high or very high landslide susceptibility classes, which suggests further management of slope stability is required for this key trade route connecting China and Pakistan to truly achieve sustainable development (Kreutzmann, 2009).

The work in this special issue addressing Challenge 1 shows how new methods to compile databases of landslide occurrence and impact can be applied in the Global South. Preliminary findings suggest that further understanding of landslide physical process within transportation corridors is required, which special issue papers in Challenge 2, in the next section, address.

2.2 Challenge 2: better understanding of links between landslide susceptibility and physical processes

A second challenge for understanding landslide–transport network interactions is that of understanding the links between landslide susceptibility and physical processes. Landslide susceptibility maps indicate where landslides are more or less likely to occur and thus underpin our understanding of transport network exposure to landslides. They can be created before a transportation corridor is built to aid planning or after building to understand which parts of the network are most exposed to landslides.

Reichenbach et al. (2018) show that since the 1980s there has been inertia in the input thematic variables and methods used, and often justification of methods is unclear, suggesting innovation is required. With regard to innovation in landslide susceptibility–transport network interactions, we argue that the treatment of transportation corridors as a separate susceptibility map is useful for understanding the local processes unique to transportation corridors. This means departing from the typical approach of developing regional-scale susceptibility maps where linear distance to roads is one of several thematic variables used.

In McAdoo et al. (2018) (addressing Challenge 3 in this special issue) they show that there is not a linear relationship between distance from a road and number of landslides observed. Reichenbach et al. (2018) argue that the physical processes and geomorphological settings do not follow linear patterns as we move away from roads. We argue the buffer zone around a transportation corridor is a unique and heterogeneous space, with some areas increasing landslide susceptibility (e.g. through poor drainage or slope modification) and other areas potentially decreasing landslide susceptibility (e.g. through remediation measures), and that these processes change over time. Four papers in this special issue attempt to address components of this complex challenge in different ways:

- Jeon et al. (2018) use 3D modelling to investigate the problem of leaky pipes causing subsidence in the cavity alongside railways, finding complex interactions between groundwater levels and distance between pipelines and roadbeds.

- Bordoni et al. (2018) develop a non-linear model of landslide susceptibility that explicitly models the connectivity of the landscape topography for allowing sediment to flow over a surface. For their study area, they found that the highest susceptibility portions of the road network appeared to be influenced by high sediment connectivity and steep slopes with a limited height, regardless of land use.

- Tseng et al. (2018) develop a mountain road susceptibility map for typhoon-triggered landslides in Taiwan and also investigate the characteristics of landslides in their inventory in relation to roads. Their findings highlight a number of processes: (i) landslides tend to be smaller in size within 100 m from the road, (ii) landslides occurring above mountain roads (i.e. between the road and the mountain ridge) tend to occur close to the road but did not increase in number after the typhoon, (iii) landslides occurring below mountain roads (i.e. between the road and the stream divide) tend to be more active following the typhoon. Changes to landslides below roads are attributed to changes in drainage from the road, a growing issue widely observed in other climate and geomorphologic contexts (Penna et al., 2014). More work is needed in this area, for which Tseng et al. (2018) provide methods to quantify and analyse different processes acting within the locality of roads.

- Meneses et al. (2019) also support our argument that the zone around roads needs special consideration. They constructed two landslide susceptibility maps: one with detailed local data and one with generalised land cover from CORINE, finding that the susceptibility map with the detailed land cover datasets performed better.

The papers in this special issue addressing Challenge 2 highlight the complex, site-specific processes determining landslide susceptibility in transportation corridors and propose a range of approaches for different settings. Special issue papers addressing Challenge 3, in the next section, build on Challenge 2 by discussing the unique setting of mountain roads.

2.3 Challenge 3: approaches to deal with the unique setting of mountain transport networks

Mountainous areas are unique in terms of their transportation networks and thus require different approaches from transportation research on urban and low-lying areas. This uniqueness stems from steep topography making building more challenging – resulting in a lower-density population served by a less dense network of smaller roads. The propensity of steeper topography to landslides (and future climate change affects landslide triggering) amplifies the problem of landslide–transport network interactions, as a network with less redundancy increases the likelihood of isolation in the event of a landslide disruption. Three of the papers in this special issue (McAdoo et al., 2018; Schlögl et al., 2019; Sudmeier-Rieux et al., 2019) address the challenge of mountain transportation networks:

- Schlögl et al. (2019) and Sudmeier-Rieux et al. (2019) emphasise the dependence of local communities on local transportation networks at both ends of the spectrum of economic development in their studies of Austria and Nepal, respectively.
- Schlögl et al. (2019) illustrate the potential for using agent-based traffic models to understand the impacts to mountain communities from road blockages at a fine spatial scale, revealing issues such as long daily commutes and dependence on specific industries (e.g. tourism).
- McAdoo et al. (2018) observe that in Nepal, where there are areas with more agricultural development (and thus a greater density of informal, minor roads), there are twice as many landslides within 100 m from the road network compared to in non-agricultural areas.

Each of these three special issue papers (McAdoo et al., 2018; Schlögl et al., 2019; Sudmeier-Rieux et al., 2019) highlights the issue that regional, major roads are given greater research attention, but local roads may be built and maintained poorly, challenging the livelihoods of local communities. Their work highlights the need to bring together research on economic development, road building and landslides and understand the bi-directional relationships between these factors. In the next section, Challenge 4, special issue papers present commentary and potential methods for looking at how management and development of mountain roads may change in the future.

2.4 Challenge 4: future drivers of landslide–transportation network interactions

The fourth research challenge we highlight is better understanding of future drivers of landslide–transportation network interactions. Three papers in this special issue address this challenge:

- Sudmeier-Rieux et al. (2019) (invited commentary) discuss trade-offs between expanding the road network of Nepal for economic development and the associated increase of landslide risk. There was a 1200 % increase in the local road network between 1998 and 2016 in Nepal (DoLIDAR, 2016), and Sudmeier-Rieux et al. (2019) indicate that many of these roads are poorly constructed and become seasonally blocked by landslides, perhaps resulting in overall losses to the community reliant on those roads. Sudmeier-Rieux et al. (2019) highlight the ongoing decentralisation of power and the China Belt and Road Initiative as governance opportunities to improve practices of road construction.
- Li et al. (2019) highlight the rapid expansion of highways in China and the associated issue of exposing bare soil and subsequent erosion. Citing previous work by Wang (2006) for every kilometre of highway built, 0.05–0.07 km^2 of soil is exposed, causing 450 t of soil loss per year in China (Chen et al., 2010). Combined with rapid expansion of the road network and climate change, the contribution of highway building to soil loss could be significant. Using the Revised Universal Soil Loss Equation (RULSE), Li et al. (2019) show that under 20-year return period conditions, 7.1 % of slopes are considered high or extremely high risk of soil erosion.
- Schlögl and Matulla (2018) use a downscaled climate projection of rainfall to examine the risk of rainfall-triggered landslide events to the road and rail network of central Europe. They show that for low-lying areas, the change in rainfall (and thus landslide triggering) is relatively low. However, areas with higher elevation may experience at least 14 additional rainfall triggering events per year, and these changes can be expected in the near future. Using the case study area of the Black Forest mountains, they show that areas of steep topography tend to have lower density transport networks with less redundancy (i.e. alternative routes in the case of a landslide) in addition to higher landslide susceptibility and a greater increase in the number of landslide-triggering rainfall events, and thus this should be prioritised for planning.

The papers addressing Challenge 4 in this special issue highlight the competing demands (and potential feedbacks) between road building, economic development, climate change and landslides. Evidence in these papers indicates that integrated planning is required to ensure that the benefits of road building are not outweighed by increased impacts from landslides, especially considering that other papers in this special issue have highlighted the need for further understanding of the physical processes driving landslides within transportation corridors.

3 Conclusions

The papers in this special issue have each addressed one or more of the research challenges to better understanding landslide–transport interactions (access to records, links between landslide susceptibility and physical processes, uniqueness of mountain transportation networks, future drivers of interactions). Collectively, the 11 papers in this special issue also highlight the need for further research beyond the four challenges discussed here and point towards potential approaches:

- better *databases of landslide impact to transportation networks*, potentially using grey literature sources such as newspapers and highway maintenance reports;
- more *detailed assessment of landslide susceptibility along transportation corridors*, using more detailed datasets and physically based models;
- better *characterisation of landslides within transportation network corridors* leading to a better understanding of physical processes, potential methods including spatio-statistical analysis of landslide inventories;
- regional *assessment of the interactions between transportation network building, economic development, climate change and landslide impacts* using agent-based traffic models and spatio-statistical analysis of roads and landslide inventories.

The majority of papers in this special issue focus primarily on road networks, but as discussed in the introduction, many other types of transportation network exist, and methods developed in the special issue papers may be applicable to additional transportation networks. Looking forward, transportation networks are crucial agents of development, enabling the flow of goods, people, services and ideas across the globe. To achieve the sustainable development goals by 2030 and lift 700 million people out of extreme poverty (World Bank, 2018), it is likely that transportation networks will need to expand rapidly in the coming decades. To ensure that transportation networks do not expose people and property to new landslide risk and the gains outweigh any losses from additional landslide impact, further research is required on landslide–transportation network interactions. The selection of papers in this open-access special issue highlights innovation in understanding of the landslide–transportation network physical process, data collection, modelling, spatio-statistical analysis and impact modelling under future climate change.

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